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PREDICTION OF ATRAZINE FATE IN RIPARIAN BUFFER STRIPS SOILS USING THE ROOT ZONE WATER QUALITY MODEL

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ABSTRACT

The Root Zone Water Quality Model (RZWQM) was used to simulate the movement of atrazine after entry into switchgrass (*Panicum virgatum* L.) Riparian Buffer Strips (RBS). A multi-species RBS located along Bear Creek, Iowa, was used as the basis for model inputs and simulation. Atrazine entered the RBS at rates representing atrazine loss in runoff of 1, 3, and 5% of a 1.5-kg ha^{-1} application to an adjacent cornfield. Water equivalent to runoff depths of 0.125, 0.25 and 0.5-cm from the adjacent cornfield was added to the natural rainfall to allow the model to simulate surface water entering the RBS. RBS retained about 79-94% of atrazine in runoff from the adjacent cornfield. The RZWQM predicted very low atrazine concentrations in seepage (< 3-µg L^{-1}). Atrazine loss in runoff leaving the RBS was most sensitive to macropore size and plant residue, but less sensitive to soil organic matter content. At macropore sizes larger than 0.01-cm there was no atrazine in runoff leaving the RBS. Plant residue mass was directly proportional to atrazine loss in runoff, but organic matter content was inversely proportional to atrazine loss in runoff. The RZWQM needed more improvement in pesticide leaching transport, and pesticide loss in runoff components.

KEYWORDS: Atrazine, Riparian Buffer Strips, Root Zone Water Quality Model

INTRODUCTION

Riparian buffer strips (RBS) are considered to be one of the best management practices to reduce the non-point source pollution from agricultural production (Arora et al., 1996; Fawcett, 1998). RBS are located between the water body and agricultural areas and have several beneficial effects (Debano and Schmidt, 1989), such as the stabilization of stream banks, and removal of sediment, nutrients (N and P), and pesticides from the surface runoff (Lowrance et al., 1984b; Cooper and Gilliam, 1987).

Atrazine (6-chloro-*N*-ethyl-*N*- (1-methylethyl)-1,3,5-triazine-2, 4-diamine) has been extensively used in the corn (*Zea Mays L.*) production and is frequently detected in the surface water and groundwater. Atrazine concentrations in surface and groundwater close to or greater than the Maximum Contaminant Level (MCL) for drinking water of 3-µg L^{-1} (USEPA, 1990a) are causes of concern over the human and animal health.

Fate of pesticides in the environment can be monitored in field studies over a long period of time. Computer simulation modeling is an interesting alternative to field studies since simulations take less time, are more economic (less costly) and do not rely on the weather. There are many existing models that can be used to simulate the persistence and the movement of chemicals in the soil profile, including the Pesticide Root Zone Model (Carsel et al., 1984) and the Groundwater Loading Effects of Agricultural Management Systems Model (Leonard et al., 1987).

Erosion control by vegetative buffer strips was tested for the effectiveness by using Chemical, Runoff, and Erosion from Agricultural Management Systems (CREAMS) (Williams and Nicks, 1988). Their results revealed that CREAMS could be used as a tool for evaluating filter strip effectiveness in reducing sediment yields.

Root Zone Water Quality Model (RZWQM) was developed by the scientists from USDA-ARS to response the need of scientists and action agencies working in the agriculture area (USDA-ARS, 1995). It is a one-dimensional model capable of simulating the fate and movement of water, nutrients and pesticides in the soil-plant-atmosphere environment by integrating physical, chemical and biological processes in the root zone. It also can simulate the effects of agricultural management practices on movement of soil, water and solute that may cause surface and groundwater quality problems (Ahuja et al., 1996). Descriptions of the model can be found in the RZWQM Technical and Manual Documentation (USDA-ARS; 1992 and 1995). A good brief review of the model also can be found in Ahuja et al. (1993), Singh et al. (1996) and Kumar et al. (1998). The effectiveness of RZWQM in simulating the pesticide movement in the soil profile had been studied by number of researchers. For example, RZWQM was found to effectively simulate distribution and movement of atrazine in the soil profile of Watkinsville, Georgia (Ma et al., 1995). Kumar et al. (1998) reported that RZWQM showed good potential for simulating atrazine losses with subsurface drain water as affected by tillage practice. Research by Azevedo et al. (1997) demonstrated that RZWQM correctly predicted depth of atrazine penetration, but overpredicted atrazine concentration in an Iowa soil profile. Recently, number of researchers evaluated RZWQM using field-measured data from various sites (Farahani et al., 1999; Ghidney et al., 1999; Jaynes and Miller, 1999; Landa et al., 1999; Martin and Watts, 1999; Wu et al., 1999). In general, the researchers were satisfied with RZWQM performance, but some suggestions were made to improve the model performance. For example, Jaynes and Miller (1999) evaluated RZWQM performance against crop yield and water, nitrate, and herbicide fate and transport during four years of a corn-soybean rotation at an Iowa MSEA site. They suggested that RZWQM needed further evaluation over a wide range of conditions to thoroughly test its robustness. Ghidney et al. (1999) suggested that RZWQM should include the capability to predict variable soil cracking based on soil moisture to improve the predictions of agricultural losses to runoff and seepage.

Previous research has shown that the use of RZWQM for simulating the pesticide and movement in the soil profile produces reasonable results. However, there is no research using RZWQM or any existing model to simulate the movement of pesticides within the RBS. The objectives of this study were to use RZWQM as a tool to predict the efficiency of the RBS removal of atrazine and atrazine fate after entering the RBS. The simulations utilized measured and estimated data from a field site in central Iowa in conjunction with local weather scenarios. Some input parameters were estimated from the literature. The movement of atrazine in the RBS soil profile was examined under a worst-case scenario, where intense rainfall generated varying amounts of atrazine loss in runoff from the cornfield to the RBS.

MATERIALS AND METHODS

Site description

The multi-species riparian buffer strip located along Bear Creek, approximately 2.4 km north of the town of Roland in Story County, Iowa, (Simpkins and Schultz, 1993) was used as the basis for model inputs and simulation. The Bear Creek watershed is situated within the Des Moines Lobe landscape, the depositional remnant of the late Wisconsin glaciation in Iowa (Schultz et al., 1995). The five-year-old switchgrass buffer strips (age in 1998) and cropped areas (corn-soybean rotation) are located on the Strum Farm in the southern half of the Bear Creek channel system.

The elevation of the site is 318 m. The aspect from true north is 200 degrees and the latitude is 42 degrees. The slope of the field is 5.71 degrees. These values were estimated by GIS (ArcView Version 3.2) based on the USGS Digital Elevation Model Data.

Meteorological data

Climatic data for the Bear Creek site were not available. Therefore, we used Walnut Creek meteorological data, which is located about 30 km from the Bear Creek site. RZWQM requires breakpoint rainfall data.

Breakpoints are obtained from the data where there is a substantial change in slope of the graph plotted between cumulative rainfall and time. Daily rainfall of the year 1993 in Walnut Creek watershed were provided by D.B. Jaynes (personal communication).

The model requires daily air temperature (minimum and maximum), wind speed, short wave radiation, and relative humidity data. An average monthly temperature at the study site were also provided by D.B. Jaynes (personal communication).

The model requires the albedo of dry soil, albedo of wet soil, albedo of crop at maturity, and albedo of fresh residue. Albedo is the refraction of incoming solar radiation reflected by the surface. Albedo dry and wet values, 14% and 8%, respectively, for chernozen soil were used in our study. These values were obtained from Jury et al. (1991).

Physical and hydraulic properties

Soil at these two sites are mapped in the Clarion-Webster-Nicolet association with minor areas of Clarion-Storden-Coland and Canisteo-Okoboji-Nicolet association (USDA, 1975). The A horizon is typically clay loam or silty clay loam. The C horizon ranges from sandy loam to clay loam, but includes layers ranging from silty clay to loamy sand (DeWitt, 1984).

The depth of both soil profiles (RBS and cornfield) in this simulation was set at 2.91-m. Profiles were divided into 8 layers (Table 1). Soil bulk density, fractions of sand, silt and clay for the first two layers (0-0.15 and 0.15-0.30 m) of RBS and cornfield were measured in a previous study at these sites (Reungsang, 2000). Texture and porosity data for the remaining layers were obtained from a profile description obtained during installation of well S-30 (Johnston, 1999), which was about 5-m from our site.

The RBS soil was set to have macropore size of 0.01-cm and macroporosity of 0.056-cm^3 cm^{-3} (Logsdon, personal communication). These unpublished values were derived from the mean macropore size and macroporosity for soils in the Clarion-Webster-Nicollet- Catena determined by using rotated core and image analysis (Logsdon et al., 1990; Logsdon et al., 1993). Several assumptions were made, including that the fraction of dead end macropore was 0.5 and that the soil profile had homogeneous properties (macropore size, total macroporosity, fraction of dead-end macropores, and fraction microporosity of total porosity) with depth. In this simulation, the cornfield soil was assumed to have no macropores because of the moldboard-plow tillage practice.

This simulation assumed there were 2 metric tons of plant residues on the RBS surface at the beginning of the simulation. Wheat residue was chosen as a substitute for switchgrass residue, because there are only 3 residue options in the model (wheat, corn and soybean). Wheat residue was considered to be most similar to switchgrass residue.

We supplied only the soil hydraulic conductivity and field capacity content at 1/3 bar. Soil hydraulic conductivities of 3.56-cm hr^{-1} and 2.92-cm hr^{-1} for the RBS soil and cornfield soil, respectively, was used as homogeneous inputs for each depth of the soil profile. These values were taken from a previous study at these sites (Reungsang, 2000). The field capacity water content of 0.22-cm^3 cm^{-3} was obtained by regression equations described by Sharpley and Williams (1990).

Organic matter

To initialize organic matter pools the model requires soil organic matter or microbial population data. Since we knew organic C content of the surface (0-0.15 m) and subsurface (0.15-0.30 cm) depths of the RBS and cornfield soils, we calculated organic matter from organic C. We assumed that the organic matter for the rest of the soil profile (the third layer to the eighth layer) were half of the previous layer. We did not have field measurements for the microbial pools; therefore the estimation number from the model was used.

To allow these pools to reach a dynamic steady state the model was run through 10 years of Walnut Creek meteorological data and then reinitialized with the values of these pools at the end of 10 year. This process was repeated for 5 times until the organic matter and microorganism pools stabilized. Then these steady-state values were used throughout the simulation as the initial state for both soil organic matter and microbial pools.

Table 1 showed the organic matter values for the RBS and cornfield soils after equilibration did not match the input (measured) organic matter values. We speculated that the difference was due to the quickturf submodule that we used in this simulation is not a detailed plant production model; it only provides inputs to the rest of the model that there is a crop growing.

Simulation of atrazine transport

The focus of this simulation was on the movement of atrazine after entering the RBS. RBS receive runoff from adjacent cropped areas. Our simulation assumed that the cornfield area contributing runoff to the RBS was 30 times larger than (30:1) the RBS area. Since RZWQM does not simulate runoff from adjacent fields, we estimated the total runoff water volume leaving the cornfield by assuming 0.125, 0.25, on 0.5-cm of runoff water from the cornfield which yielded 3.75, 7.50, and 15-cm of water entry the RBS, respectively. Estimated runoff volume was then added to the natural rainfall data in the meteorological data file. Due to the inability of the model to generate runoff water with long rainfall duration time, we confined the natural rainfall plus simulated runoff to a short 4-minute period to obtain high rainfall intensity. This approach allowed the model to generate the runoff leaving RBS.

Atrazine was loaded into the RBS using the surface broadcast application option in RZWQM on the same day that rainfall plus simulated runoff event occurred (Julian day of 189, 1993). The amount of atrazine entering the RBS was assumed to be 1, 3, and 5% of atrazine applied to the cornfield, which yielded 0.45, 1.35 and 2.25-kg ha^{-1} loading rates. A 5% loss of atrazine in runoff from cornfield was assumed to represent the worst-case pesticide loss, which might occur when runoff occurs soon after pesticide application (Wauchope, 1978; Leonard, 1982). Runoff depth of 0.5-cm from the field is a typical runoff depth from a single storm event. The fate of atrazine in the cornfield soil was also simulated. The properties of atrazine used in this simulation were shown in Table 2. We assumed that there was residual atrazine of 10-μg L^{-1} in the first layer (0-15 cm depth) of cornfield soil at the beginning of the simulation but there was no residual atrazine in RBS soil. Atrazine rate was surface broadcast applied to cornfield at the rate 1.5-kg ha^{-1}.

The Quickturf submodule was used to simulate growth of switchgrass under our specified environmental and management practices. This model is not a detailed plant production model; it only provides inputs to the rest of the model that there is a crop (i.e., switchgrass in our study) growing (K.W. Rojas, personal communication). We noted that to use quickturf submodule we need to specify the operation date before the simulation period because the grass is a perennial (continuous growth) and does not require planting like an annual crop (e.g., corn). Table 3 showed the details of management practices in the RBS and cornfield.

RZWQM98 Window version (version 1.0.99.61) was used through out the study. This version is more user friendly than the DOS version and allows easy manipulation of input data in each window session.

RESULTS AND DISCUSSIONS

Simulation of atrazine fate, leaching and runoff loss

As atrazine load into the RBS and the runoff depth from the cornfield increased the atrazine mass loss in runoff leaving the RBS increased (Table 4). Atrazine mass in runoff leaving the RBS were in the range of 6 to 21% of the amount entering the RBS. This implied that even under a worst-case scenario, the RBS showed the capability to reduce approximately 79 to 94 % of atrazine in the runoff water from the cornfield. Fawcett et al. (1995) compiled published data from buffer strip studies (46 data points) and found buffer strips reduced herbicide in runoff by an average 48% with a range of herbicide removal 9 to 91%. Fawcett et al. (1995) suggested that herbicide removal could be overestimated in some studies because the research was done with small scale VBS. The RZWQM predicted that 66% and 57% of atrazine was trapped in the first 0-0.15 m soil depth of the RBS (day 189) and cornfield soils (day 107), respectively (Table 5). Organic C in the first 0-0.15 m of both soils was much higher than the organic C at deeper depths (Table 1). Soil with higher organic C can sorb atrazine more readily than low organic C soils. The majority of the atrazine entering the RBS was retained in the surface 15 cm of soil. Table 5 showed representative results for one set of simulations. Model predictions of atrazine mass decreased over time due to microbial degradation, plant uptake, volatilization, and leaching processes (Figure 1).

The atrazine in the subsurface soil (0.05-0.15 m) showed an increasing trend in the RBS soil up to day 240, then began to decrease (Table 5). The increase in atrazine mass in subsurface soil during the period after atrazine entry into the RBS was due to downward movement of atrazine from the top layer of soil. The RZWQM predicted that most of atrazine was in the top 0-0.15 m depth (Table 5) with < 1-μg kg^{-1} of atrazine at deeper depths. These predicted concentrations were very low and contrast from atrazine concentrations in soils from Walnut Creek watershed reported by Moorman et al. (1999). They reported that average atrazine concentrations over the entire season for 0-7.5 cm, 7.5-15, 15-30, and below 45-cm depth were 47, 15.5, 5.5 and <1-μg kg^{-1}, respectively. Our simulation results for the cornfield soil can be compared to the Walnut Creek data (Moorman et al.,1999) and suggest that movement of atrazine to deeper soil layers is underestimated by RZWQM.

Since the model predicted that most of the atrazine was trapped in the surface (0-0.15 m) of RBS soil profile, with little movement to the 15-30 cm depth, it also predicted very low concentrations (<3-μg mL^{-1}) of atrazine in seepage (Table 6). Seepage is the water passing through the macropores and soil matrix at the bottom of the soil profile. These very low atrazine concentrations in seepage predicted by RZWQM (Table 6) appear to be less than what would be expected from studies on similar landscapes in Iowa. Jaynes et al. (1999) found atrazine in subsurface drainage water rapidly increased after rainfall events. Moorman et al. (1999) reported 1.4% of the groundwater samples beneath the subsurface drains in Walnut Creek watershed contained atrazine greater than the MCL level and 30% contained atrazine concentrations above the 0.2-μg L^{-1}. Predicted atrazine concentrations in the seepage under the RBS were many orders of magnitude below 1-μg L^{-1}. This may be due to the fact that there was no residual atrazine in the RBS soil profile at the beginning of the simulation. Burkart et al. (1999) reported that the antecedent concentrations of atrazine in soil were important to conduct accurate short-term simulations by the Pesticide Root Zone Model (PRZM).

Atrazine trapped in the RBS soil and cornfield soil was degraded over time (Figure 1). Atrazine half-life in the RBS soil and cornfield soil predicted by RZWQM model were calculated by the first order kinetic model: $C = C_0 e^{-kt} + Y_a$, where C is the concentration of atrazine as a function of time in days (μg kg^{-1}), C_0 is the initial atrazine concentration (μg kg^{-1}), k is the rate constant (day^{-1}), t is time (days) and Y_a is an asymptotic estimate of the concentration of atrazine that degrades very slowly over time (residual atrazine). Predicted atrazine half-lives calculated from the model results were 21 days and 11 days for the RBS surface soil (0-30 cm) and cornfield surface soil (0-30 cm), respectively. These half-lives valued were slightly shorter than the actual half-lives (27 days for the RBS soils and 17 days for corn soils), calculated for 0-30 cm soil depth from a previous research conducted using soils from these sites (Reungsang, 2000), which we used in the RZWQM input file (Table 3). The differences may be explained by the fact that some of the soil parameters in the model input files were obtained from the literature instead of the measured data. Pesticide fate is strongly related to the site-specific values, therefore the measured parameters are needed to precisely predict pesticide fate in soil.

Retention of pesticides in the RBS has been attributed to infiltration and sorption (Hall et al., 1983; Arora et al. 1996; Mickelson and Baker, 1993). Previous studies have identified organic matter content and macroporosity as important factors in the infiltration and sorption processes. In addition we measured high sorption coefficients for plant residues in VBS (Reungsang, 2000), and suggested that plant residues might retain pesticides. We conducted a set of simulations varying these factors. Simulation results showed that by increasing macropore size by the factor of 10 (from macropore size of 0.01-cm to 0.1-cm) eliminated atrazine in runoff leaving the RBS (Table 7). This appeared to be due to the fact that the model routed water and atrazine through the macropores in the soil profile. However, measured macropore diameter in soils range between 0.05 to greater than 1 cm (Miller and Gardiner, 1998). We found that simulations with smaller macropore sizes produced more atrazine loss in runoff (Table 7). Macropore sizes larger than 0.01-cm increase seepage flow, but RZWQM simulations do not show a corresponding increase in atrazine leached (data not shown).

Atrazine loss in runoff leaving the RBS was proportional to plant residues mass (Table 7), suggesting that atrazine washed off from crop residues is an important process. Martin et al. (1978) reported that atrazine, alachlor, cyanazine and propachlor were not strongly adsorbed to corn residue and were washed off rapidly with water. In contrast, Baker et al. (1982) found that crop residue reduced herbicides loss in runoff because crop residues delayed and reduced surface runoff.

Simulation results showed that soil organic matter content was inversely proportional to atrazine loss in runoff leaving the RBS (Table 7). This was due to the fact that soils with high organic matter content sorb pesticide to a greater extent than soils with low organic matter content.

CONCLUSIONS

The simulation results suggested that:

1) The RZWQM predicted 79-94% of atrazine in runoff from the adjacent cornfield was retained in the RBS.
2) The RZWQM predicted very low atrazine concentrations in seepage. Based on a comparison of our model results for atrazine applied to cornfield to the studies from nearby Walnut Creek, we suggested that RZWQM underpredicted leaching in the soil profile. Further modifications of the leaching subroutine are needed to correctly predicted pesticide loss in the seepage.
3) Simulation results suggested that atrazine lost in runoff leaving the RBS were sensitive to macropore size and the amount of plant residues but were less sensitive to soil organic matter content. However, further study of the relationship between macroporosity and runoff losses of pesticides are needed to verify the model sensitivity to macropores.

REFERENCES

Ahuja, L.R., DeCoursey, D.G., Barnes, B.B., and Rojas, K.W. (1993) Characteristics of macropore transport studied with the ARS Root Zone Water Quality Model., *Trans. ASAE*. Vol.36:369-380.

Ahuja, L.R., Ma, Q.L., Rojas, K.W., Boeston, J.J.T.I., and Farahani, H.J. (1996) A field test of Root Zone Water Quality Model-pesticide and bromide behavior., *Pestic. Sci*. Vol.48:101-108.

Arora, K., Mickelson, S.K., Baker, J.L., Tierney, D.P., and Peters, C.J. (1996) Herbicide retention by vegetative buffer strips from runoff under natural rainfall., *Trans. ASAE*. Vol.39:2155-2162.

Azevedo, A.S., Kanwar, R.S., Singh, P., Ahuja, L., and Pereira, L.S. (1997) Simulating atrazine transport using RZWQM for Iowa soil profile., *J. Environ. Qual*. Vol.26:153-164.

Baker J.L., Laflen, J.M., and Hartwig, R.O. (1982) Effects of corn residue and herbicide placement on herbicide runoff losses., *Trans. ASAE*. Vol.25:340-343.

Burkart, M.R., Gassman, P.W., Moorman, T.B., and Singh, P. (1999) Estimating atrazine leaching in the Midwest., *J. Am. Water Res. Assoc*. Vol.35: 1089-1100.

Carsel. R.F., Smith, C.M., Mulkey, L.A., Dean, J.D., and Jowise, P.P. (1984) Users manual for the pesticide root zone model (PRZM), release 1. EPA-600/3-84-109. Athens, GA:USEPA.

Cooper, J.R., and Gilliam, J.W. (1987) Phosphorus redistribution from cultivated fields into riparian areas., *Soil Sci. Soc. Am. J.* Vol.51:1600-1604.

Debano, L.F., and Schmidt, L.J. (1989) Improving southwestern riparian areas through watershed management, In: *USDA Forest Service,* Rocky Mountain Forest and Range Experiment Station (ed.). General technical report. Fort Collins, CO. pp. 1-24.

Dewitt, T.A. (1984) Soil Survey of Story County, Iowa, United States Department of Agriculture, Soil Conservation Service.

Farahani, H.J., Buchleiter, G.W., Ahuja, L.R.,. Peterson, G.A, and Sherrod, L.A. (1999) Seasonal evaluation of the Root Zone Water Quality Model in Colorado., *Agronomy J.* Vol. 91:212-219.

Fawcett, R.S. (1998) The role of best management practices in reducing triazine runoff. In: *Triazine herbicides risk assessment,* L.G. Ballantine, McFarland, J.E. and Hackeh, D.S. (eds.), ACS Symp. Ser. No. 683. Am. Chem. Soc., Washington, DC. pp. 49-58.

Fawcett, R.S., Tierney, D.O., Peter, C.J., Baker, J.L., Mickelson, S.K., Hatfield, J.L, Hoffman, D.W., and Franti, T.G. (1995) Protecting aquatic ecosystem with vegetative filter strips and conservation tillage. Proc. Natl. Agric. Eco. Manage. Conf., New Orleans, LA.

Ghidney, F., Alberts,, E.E., and Kitchen, N.R. (1999) Evaluation of the Root Zone Water Quality Model using field-measured data from the Missouri MSEA., *Agronomy J.* Vol.91:183-192.

Hall, J.K., Hartwig, N.L., and Hoffman, L.D. (1983) Application mode and alternative cropping effects on atrazine losses from a hillside., *J. Environ. Qual*. Vol.36-340.

Jaynes, D.B, and Miller,J.G. (1999) Evaluation of the Root Zone Water Quality Model using data from the Iowa MSEA., *Agronomy J*. Vol. 91:192-200.

Jaynes, D.B., Hatfield, J.L, and. Meek, D.W. (1999) Water quality in Walnut Creek watershed: Herbicides and nitrate in surface water., *J. Environ. Qual*. Vol.28:45-59.

Johnston, D.A. (1998) Hydrogeology and geology of three restored riparian buffers near Roland, Iowa. M.Sc. Thesis, Department of Geology and Atmospheric Sciences, Iowa State University, Ames, Iowa.

Jury, W., Gardner, W.R., and Gardner, W.H. (1991) Soil Physics. John Wiley & Sons, New York.

Kumar, A., Kanwar, R.S., and Ahuja, L.R. (1998) Evaluation of preferential flow component of RZWQM in simulating water and atrazine transport to subsurface drains., *Trans. ASAE*. Vol.41:627-637.

Landa, F.M., Fausey, N.R., Nokes, S.E., and Hanson, J.D. (1999) Plant production model evaluation for the Root Zone Water Quality Model (RZWQM 3.2) in Ohio., Agron. J. Vol.91:220-227.

Leonard, R.A., Kinsel, W.G, and Still, D.A. (1987) GLEAMS: Groundwater loading effects of agricultural management systems., *Trans. ASAE.* Vol.30:1403-1418.

Logsdon, S.D., McCoy, E.L., Allmaras, R.R., and Linden, D.R. (1993) Macropore characterization by indirect methods., *Soil Science*. Vol.155:316-324.

Logsdon, S.D., Allmaras, R.R., Wu, L., Swan, J.B., and Randall, G.W. (1990) Macroporosity and its relation to saturated hydraulic conductivity under different tillage practices., *Soil Sci. Soc. Am. J.* Vol.54:1098-1101.

Lowrance, R.R., Todd, R.L., Fail, J., Hendrickson, O., Leonard, R., and Asmussen, L. (1984) Riparian forests as a nutrient filters in agricultural watersheds., *Bioscience* Vol.34: 374-377.

Ma, Q.L., Ahuja, L.R., Rojas, K.W., Ferreira, V.F, and DeCoursey, D.G. (1995) Measured and RZWQM predicted atrazine dissipation and movement in a field soil., *Trans. ASAE*. Vol.38:471-479.

Martin, C.D., Baker, J.L, Erbach, D.C., and Johnson, H.P. (1978) Washoff of herbicides applied to crop residue., *Trans. ASAE*. Vol.21:1164-1168.

Martin, D.L., and Watts, G.D. (1999) Evaluation of the Root Zone Water Quality Model for conditions in central Nebraska., *Agron. J.* Vol.91:201-211.

Mickelson, S.K. and Baker, J.L. (1993) Buffer strips for controlling herbicide runoff losses., ASAE Paper No. 932084. Spokane, WA.

Miller, R.W. and Gardiner, D.L. (1998). Soil physical properties. In: *Soils in our environment,* R.W. Miller, and Gardiner, D.L. (eds.), 8th edn, Prentice-Hall Inc., NJ. pp. 82.

Moorman, T.B., Jaynes, D.B., Cambardella, C.A., Hatfield, J.L., Pfeiffer, R.L., and Morrow, A.J. (1999) Water quality in Walnut Creek watershed: Herbicides in soils, subsurface drainage, and groundwater., *J. Environ. Qual*. Vol.28:35-45.

Reungsang, A. (2000) Transport and Fate of Atrazine in Riparian Buffer Strips Soils. Chapter 4. Ph.D. Dissertation, Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, Iowa.

RZWQM Development Team. (1995) Root Zone Water Quality Model. Version 3. Technical documentation. GPSR Tech. Rep. 5. USDA-ARS, Fort Collins, CO.

Schultz, R.C., Colletti, J., Isenhart, T., Simpkins, W., Mize, C., and Thompson, M. (1995) Design and placement of a multi-species riparian buffer strip system., *Agroforestry Systems.* Vol.29:201-226.

Sharpley, A.N., and Williams, J.R. (1990) EPIC-Erosion Productivity Impact calculator. User Manual. USDA-ARS Tech. Bull. 1768. U.S. Gov. Print. Office, Washington, DC.

Simpkins, W.W., and Schultz, R.C. (1993) Physical setting of the constructed multi-species riparian buffer strip (CMRBS) site. In: *Water, Water, Everywhere…* Geological Society of Iowa Guidebook No. 58, pp. 99-104.

Singh, P., Kanwar, R.S., Johnsen, K.E., and Ahuja, L.R. (1996) Calibration and evaluation of subsurface drainage component of RZWQM V. 2.5., *J. Environ. Qual*. Vol.25:56-63.

U.S. Department of Agriculture. (1975) Soil Taxonomy. Agriculture Handbook 436. Government Printing Office, Washington, DC.

USDA-ARS. (1992) Root Zone Water Quality Model (RZWQM) V. 1.0. Technical Documentation. GPSR Technical Report No. 2. USDA-ARS Great Plains Systems Research Unit. Ft. Collins, CO.

USDA-ARS. (1994) Root Zone water Quality Model (RZWQM) V. 2.1 Technical Documentation Update. USDA-ARS Great Plains Systems Research Unit. Ft. Collins, CO.

USDA-ARS. (1995) Root Zone Water Quality Model (RZWQM) V. 3.0. User's Manual. GPSR Technical Report No. 5. USDA-ARS Great Plains Systems Research Unit. Ft. Collins, CO.

U.S. Environmental Protection Agency. (1990). National pesticide survey: Project summary. Office of Pesticide and Toxic Substances. USEPA, Washington, DC.

Wauchope, R.D. (1978) The pesticide content of surface water draining from agricultural fields., *J. Environ. Qual.* Vol. 7:459-472.

Williams, R.D., and A.D., Nicks. (1988) Using CREAMS to simulate filter strip effectiveness in erosion control., *J. Soil Water Conserv*. Vol.21:108-112.

Wu, L., W. Chen, J.M. Baker, and J.A. Lamb. (1999) Evaluation of the Root Zone Water Quality Model using field measured data from a sandy soil., *Agron. J.* Vol.91:177-182.

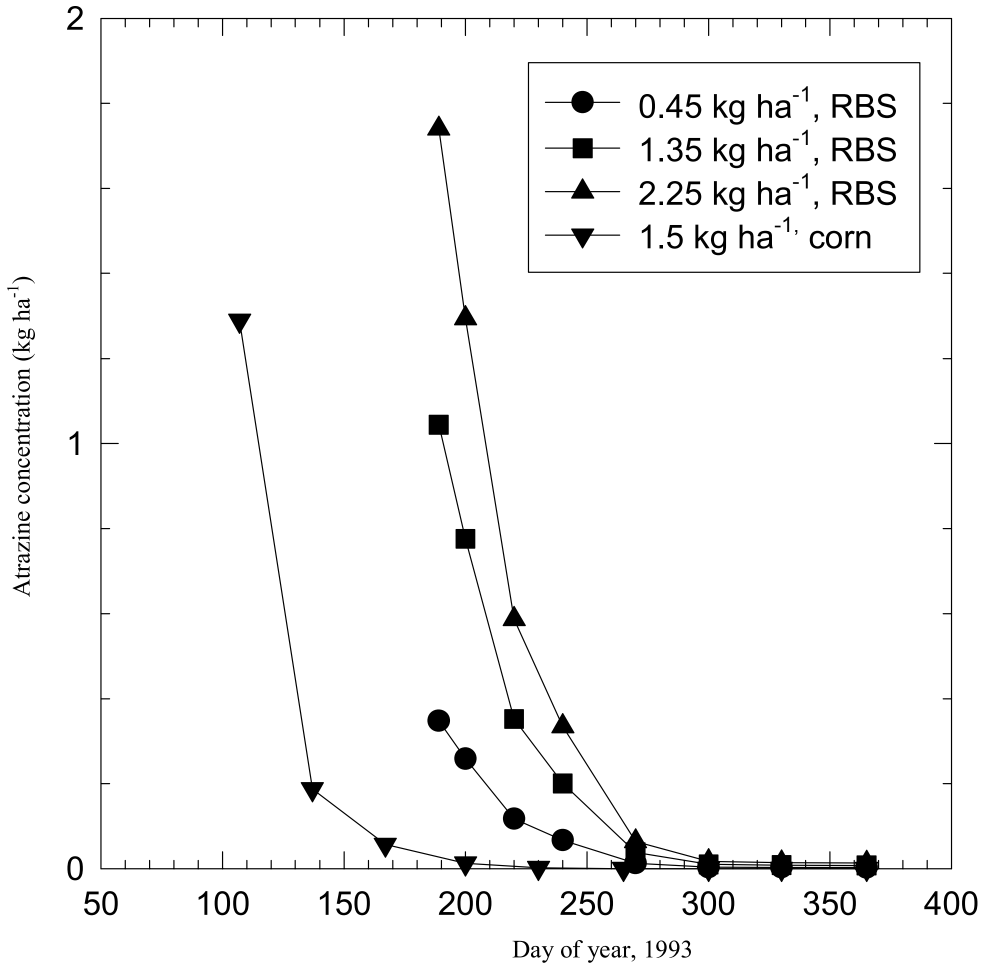

Figure 1. Simulated atrazine concentration in the RBS and the cornfield soil profiles during 1993

Table 1. Selected properties of the RBS soils and cornfield soils

Soil horizons	Depth	Sand	Silt	Clay	Organic matter*	Simulated organic matter†	Bulk density
	m		%			$g\ SOM\ g^{-1}$ soil	$g\ cm^{-3}$
RBS							
1	0-0.15	76	14	10	0.04069	0.02483	1.525
2	0.15-0.30	65	25	10	0.01224	0.00700	1.525
3	0.30-1.08	27	46	27	0.00612	0.00353	1.525
4	1.08-1.53	18	54	28	0.00306	0.00179	1.525
5	1.53-1.81	31	48	21	0.00153	0.00088	1.525
6	1.81-2.01	62	25	13	0.00077	0.00045	1.525
7	2.01-2.43	54	32	14	0.00038	0.00022	1.525
8	2.43-2.91	52	32	16	0.00019	0.00011	1.525
Cornfield							
1	0-0.15	76	14	10	0.01224	0.01180	1.31
2	0.15-0.30	74	16	10	0.01345	0.00769	1.65
3	0.30-1.08	27	46	27	0.00672	0.00388	1.65
4	1.08-1.53	18	54	28	0.00336	0.00196	1.65
5	1.53-1.81	31	48	21	0.00168	0.00099	1.65
6	1.81-2.01	62	25	13	0.00084	0.00051	1.65
7	2.01-2.43	54	32	14	0.00042	0.00026	1.65
8	2.43-2.91	52	32	16	0.00021	0.00012	1.65

* Fraction of organic matter used as the input parameters

† Fraction of organic matter obtained after the organic matter equilibration by run the RZWQM through 10 years of the climatic data, 5 times

Table 2. Atrazine properties used in the simulation

	Properties
Molecular weight, g $mole^{-1}$	215.7
Vapor pressure, mm Hg	$2.89 * 10^{-7}$
Water solubility, mg L^{-1}	33
Henry's law constant	$1 * 10^{-5}$
pk_a	1.68
Washoff foliar power, mm^{-1}	0.005
Washoff foliar fraction	100
Washoff residue power, mm^{-1}	0.005
K_{oc}*	70 (RBS soil)
	168 (cornfield soil)
Atrazine half-life, days*	27 (RBS soil)
	17 (cornfield soil)

* Values were obtained from Reungsang (2000)

Table 3. Management practices in the RBS and cornfield in 1993

Management events	RBS	Cornfield
Atrazine application date	07/08/1993	04/17/1993
Planting date	05/01/1988	05/01/1993
Planting density, plants ha^{-1}	3873600	65000
Row spacing, m	0.15	0.75
Cultivation, tillage date	No till	Moldboard plow
Harvest date, Julian day	Day 300	Day 280

Table 4. Atrazine in runoff leaving the RBS after a one-day storm event simulated by RZWQM*

Atrazine load entry into RBS	Runoff depth from cornfield	Runoff depth leaving RBS	Atrazine loss In runoff		Conc. in runoff
kg ha^{-1}	cm		kg ha^{-1}	%	μg mL^{-1}
0.45	0.125	3.62	0.0286	6.35	0.0790
	0.25	7.35	0.0545	12.11	0.0741
	0.50	14.81	0.0964	21.42	0.0651
1.35	0.125	3.62	0.0859	6.36	0.2373
	0.25	7.35	0.1635	12.11	0.2224
	0.50	14.81	0.2892	21.03	0.1953
2.25	0.125	3.62	0.1431	6.36	0.3953
	0.25	7.35	0.2725	12.11	0.3707
	0.50	14.81	0.4814	21.40	0.3251

* This simulation was performed with 2 metric tons of plant residue and macropore diameter set to 0.01-cm

Table 5. Simulated atrazine concentration (mg kg^{-1} soil) in the soil profile of the cornfield and the RBS, year 1993 ♦

Soils	Depth, m	D 107♣	D 137	D 167	D 189*	D 210	D 240	D 270	D 300	D 330	D 365
Cornfield											
	0-0.05	1.63	0.09	0.04	0.029	0.01	1.58E-3	9.37E-5	1.84E-7	2.25E-8	2.69E-12
	0.05-0.15	2.86E-3	3.89E-4	5.84E-5	1.87E-4	1.79E-4	5.87E-5	2.77E-6	1.83E-7	1.53E-12	2.24E-18
RBS											
	0-0.05	N/A	N/A	N/A	2.42	1.31	0.46	0.07	2.61E-3	1.63E-4	1.05E-6
	0.05-0.15	N/A	N/A	N/A	2.22E-5	4.04E-3	9.69E-3	3.22E-3	9.77E-5	2.73E-8	6.91E-13

♦ This simulation was performed with 2 metric tons of plant residue and macropore diameter set to 0.01 cm
♣Atrazine was applied to cornfield at the rate of 1.5-kg ha^{-1} on day 107
*Runoff depth from cornfield entering the RBS was equivalent to 0.5 cm on day 189
*Atrazine load in runoff water from cornfield to the RBS was equivalent to 2.25-kg ha^{-1} on day 189

Table 6. Cumulative atrazine mass and concentrations in seepage 53 days after entry into the RBS

Atrazine load	Runoff depth	Atrazine loss in seepage		Seepage volume
kg ha^{-1}	cm	x 10^{-36}		mL water cm^{-2} soil
		kg ha^{-1}	μg mL^{-1}	
0.45	0.125	2.79	1.16	24.08
	0.25	2.73	1.13	24.08
	0.50	2.60	1.08	24.11
1.35	0.125	8.38	3.48	24.08
	0.25	8.20	3.41	24.08
	0.50	7.81	3.24	24.11
2.25	0.125	14.0	5.81	24.08
	0.25	13.7	5.69	24.08
	0.50	13.0	5.39	24.11

Table 7. Macropore size, plant residue, and soil organic matter effects on atrazine loss in runoff leaving the RBS

Input parameter (%change)	Atrazine loss, kg ha^{-1} (%change)*
Macropore size, cm	
0.001 (-90)	0.73 (+52)
0.005 (-50)	0.63 (+30)
0.010 (0)	0.48 (0)
0.100 (+900)	0 (-100)
Plant residues, metric tons ha^{-1}	
0 (-100)	0.19 (-60)
0.5 (-75)	0.28(-42)
2.0 (0)	0.48 (0)
10 (+400)	0.86 (+79)
20 (+900)	0.92 (+90)
Organic matter content, g SOM g^{-1} soil	
0.004 (-90)	0.63 (+30)
0.010 (-75)	0.58 (+21)
0.020 (-50)	0.54 (+12)
0.041 (0)	0.48 (0)

* Atrazine entering the RBS was equivalent to 2.25-kg ha^{-1}